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Computers and Strategic Advantage: III. Games, Computer Technology, and a Strategic Power Ratio

E. W. Paxson

A Report prepared for

UNITED STATES AIR FORCE PROJECT RAND

Rand
SANTA MONICA, CA. 90406

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PREFACE

This Rand report is one of three that examine the nature and impact of U.S. computer technology relative to that of the Soviet Union, and the military advantages that the United States may be able to achieve through applications of advanced computer technology.* It addresses relationships between computer technology and strategic capabilities and presents a game theoretic model for quantifying these relationships in a form that could contribute to policy decisionmaking.

In varying degree, portions of this report should be useful to the Air Staff and to other strategic analysts in the Department of Defense, as well as to the Arms Control and Disarmament Agency.

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*See also R. Turn and A. E. Nimitz, *Computers and Strategic Advantage: I. Computer Technology in the United States and the Soviet Union*, The Rand Corporation, R-1642-PR, May 1975; and R. Turn, M. R. Davis, E. W. Paxson, and R. Strauch, *Computers and Strategic Advantage: II. Capability-Enhancing Applications*, The Rand Corporation, R-1643-PR, August 1975.

SUMMARY

Although the level of computer technology in the Soviet Union is steadily increasing, it continues to lag behind that of the United States. The computer industry in the United States and in other Western countries, stimulated by Soviet overtures, sees in this an opportunity for significant trade. On the other hand, since computer technology permeates all phases of the development, production, operation, and support of modern military systems, the most advanced computers and related hardware have been kept on the embargoed strategic goods list since the 1950s. The export controls on computers and on the more important underlying manufacturing technology are now being strongly challenged, and a debate is under way on the scale and nature of computer technology transfer to the Communist countries. A central question in the debate is whether such transfer would yield strategic advantages to the Warsaw Pact nations or, as a weaker formulation, whether strategic disadvantages to the United States and its Allies would emerge.

Game theory provides one way of quantifying such terms as "advantage," "sufficiency," and "parity." This report presents a model for measuring the cost to both sides to realize in the future (i.e., through 1982) various U.S. to S.U. strategic power ratios, in terms not of dollars and rubles but of the percentages of strategic forces that would need to be modernized, given different relative military technology levels.

It is postulated that the pervasive use of computer technology in R&D, and in the production, operation, and control of military systems, gives a positive acceleration to the overall growth rate of military technology. The relative magnitude of this acceleration for the two countries can be estimated, as an initial approximation, from the historical growth rates of computing capabilities of the two countries. United States computer technology performance, measured in terms of computing speed and memory capacity, appears to double every six years, while in the Soviet Union the level doubles every ten years.

On the basis of these growth rates, the *overall* growth in the effectiveness of weapon systems is postulated to double in the United States every 24 years and in the Soviet Union every 30 years. Any extrapolation of these growth rates into the future must, however, take into account uncertainties in respect to the size and direction of military R&D budgets.

The model constructed ascribes utility functions, which drive behavior, to the top decision levels in the United States and the Soviet Union. The United States finds *accelerating* disutility as the strategic power ratio of Soviet to U.S. forces departs from unity and approaches a "catastrophic" value of *two*. But the cost to redress an imbalance in the ratio is also a disutility. Put otherwise, reducing the power ratio is desirable but must be balanced against the increasing cost to do this.

For the Soviet Union, increasing the power ratio in its favor has decelerating increasing utility as the value *two*--considered by the Soviet Union to be an assured *disarming* deterrent--is approached. But the cost to drive the ratio up has disutility for the Soviet Union also, since there are other demands on available resources.

We will use a game theory concept under which each player tries to maximize his own utility function. The theory shows that an equilibrium point arises, such that if one player abides by his calculated force level at the equilibrium point, the other cannot do better than abide by the calculated level for his forces also.

A numerical run of the model shows that increases in the Soviet growth rate in computer technology beyond the historical rate can have significant implications for the required modernization of U.S. forces if a desired strategic power ratio is to be maintained. For example, the model shows that to have parity in 1982, the United States would need to modernize about 33 percent of its strategic forces, and the Soviet Union about 54 percent, if the Soviet technology grows at its unassisted historic rate. However, if Soviet technology were advanced to the same level as that of the United States by large scale transfers, the above numbers change to 95 percent and 74 percent, respectively. According to this model, the United States must indeed have technological superiority to compensate for numerical inferiority.

The assumptions underlying the model are spelled out, permitting criticism of it in detail. But even if the model is accepted in broad outline, the intended use must be clearly understood. It tries to formalize important factors influencing U.S./Soviet negotiatory interactions, and Congressional debate in respect to the acceptability of arms agreement proposals by examining the quantity versus quality tradeoff issue. In this sense, it is an essay on some underlying aspects of political behavior and decision. But in no way can the model be used to measure the expected outcome of actual strategic nuclear counterforce exchanges. (The report concludes by enlarging on this point.)

Finally, we note that this analysis assumes that the terms of the 1972 ABM Treaty and the Offensive Weapons Interim Agreement continue in force through this decade at least. Should these terms change, new analysis would obviously be needed.

ACKNOWLEDGMENTS

I am indebted to Lloyd Shapley for several enlightening discussions of game theory. Bruno Augenstein, Robert Klitgaard, and Ralph Strauch commented constructively and in detail on a draft. For better or worse, I rejected many of their well-taken points, while because of them being forced to make a major revision. Endorsement of the analysis by these colleagues is not implied.

CONTENTS

I. INTRODUCTION

What do people mean when they use the expressions "strategic parity," "strategic subparity," "strategic balance," "strategic sufficiency," "strategic power ratio"? Clearly, they are all grasping for some measure of risk to the nation, of deterrence of nuclear war. People in the executive branches must have *some* rationalized measure, since positions must be taken in negotiations, and strategic postures must be planned, justified, and funded.

Each person has his own perception of the meaning of the phrase he uses and those others use, and their validity in measuring risk and deterrence. The psychologist would say that, depending on the person, the particular image of nuclear war held in his right cerebral hemisphere, the domain of "hot" cognition, is inadequately and quite differently elaborated and articulated by his left hemisphere, where analytic and language skills reign, albeit somewhat warmly also. The image of war, with its felt outcome, is translated simplistically into numbers.

The semantics and pragmatics at issue are put in boldest relief by a careful reading of the legislative history* of the Jackson "strategic equality" amendment in the Congressional debate on the ABM Treaty and the Offensive Weapons Interim Agreement.

We find in summary of the debate that there is

- a tacit acceptance of the statement "without the interim agreement of 1972, the Soviet Union would have a force advantage of 3 to 2 in 1977";
- an emphasis on numbers of vehicles with the same *name* (100 ABM launchers at each of two sites for both the United States and Soviet Union, 1618 Soviet ICBM launchers versus 1054 U.S. launchers,

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* *Congressional Record*, Senate, August 3, 1972, through September 25, 1972.

44 U.S. SSBN with 710 SLBM launchers versus 62 Soviet SSBN with 950 launchers);

- a subsequent recognition that names mean different things in terms of number of RVs and throwweights;
- a lumping of warheads and yields across various systems (e.g., the United States has a 2 to 1 advantage in warheads and a 4 to 1 deficit in throwweight, but four 1-MT warheads are equivalent to one 16-MT warhead [sic]*);
- a dismissal of non-Triad elements as components of the strategic balance (NATO forces, Carrier Task Forces for the United States, I/MRBMs and Golf class boats for the Soviet Union);
- an inability to put relative technology in quantitative terms.†

In developing the ideas in this preamble, a strategic power ratio‡ will be constructed and used. However, it must be pointed out at the

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*The 1/2 power is the scaling law employed. Using a 2/3 power law for equivalent megatonnage (EMT), versus *soft* targets, would change four 1-MT warheads to 6.3. The Senators did not pursue the EMT arithmetic.

†But Senator Bellmon summed up this aspect best on August 15, 1972: "...the administration's argument on behalf of the interim agreement rests on the premise that our *advantage* in technology *balances out* the large Soviet advantage in numbers. I therefore ask the Senate to consider how strategic *equality* is to be calculated once the technological gap between ourselves and the Soviets...begins to narrow as it *necessarily* must over the next five years. Will we then be able to say that the relationship which held true in 1972 will still hold true in 1977? I think not." (Emphasis added.)

‡Economists as well as Senators use simplified ratios in their models. Gift ("Trading in a Threat System," *JCR*, Vol. 13, No. 4, December 1969, pp. 418-437) lets Z be a production flow of military hardware and assumes side A will act to maximize Z_A/Z_B and will set some minimal constraints on the *ratio*. Boulding (*Conflict and Defense*, 1962) formulates the Richardson type of reaction process by working with the ratio (and absolute values) of B's hostility to A without "stopping at this point to inquire how these quantities are measured or observed." Presumably the amount of military hardware is such a measure, since an unstable equilibrium is assumed to result in an arms race.

outset that the strategic power ratio is not to be thought of as a measure of the expected *outcome* of strategic nuclear counterforce exchanges. (The correct approach as we see it, if such outcomes are to be calculated, is sketched in the last section, where we indicate (p. 21) that in some sense, strategic outcomes *may* be monotonic with respect to power ratios.

But a power ratio is meaningful for the analyst if it describes the basis actual decisionmakers use in thinking about deterrence, negotiating, debating, and planning postures. This analysis, then, is an experimental attempt to abstract the components in the thinking of such actors, including their implicit utility functions, and to give a formalism for their behavior. The reader will make his own estimate of the artificiality of this experiment. We underline that this will not be a simulation of negotiating and legislative processes, nor will it use n-person game theory, for n greater than 2. And certainly our formulas will not be entered in the *Congressional Record*.

II. STRATEGIC FORCE EFFECTIVENESS

Make a basic assumption about the future. Instead of measuring strategic power by equivalent megatonnage, which amounts to assured destruction war against soft targets (cities), people will think more and more in terms of counterforce war.* In simplest terms, this means the capability to kill hard or point targets. We shall, therefore, zero in with Barbieri† on countermilitary potential (CMP), defining it for a given weapon to be

$$\mathrm{CMP} = (Y)^{2a}/(\mathrm{CEP})^2 ,$$

where Y is the yield in megatons, CEP is in thousands of feet, the scaling exponent $a = 1/3$ for $Y > 0.2$ MT, and $a = 2/5$ for $Y < 0.2$ MT. Barbieri then gets an overall measure of offensive capability by summing the CMPs across all weapons in all vehicles of the Triad, using appropriate yields and CEPs.

It is conceptually convenient to introduce next a "homogenized" strategic force unit. We suppose that because of Soviet MIRVing and other improvements since 1972, as of the end of 1974, the Soviet Union has $n = 1500$ force units of three warheads each, of average yield y, drawn as an average mix from Triad members.‡ The United States has $N = 1000$ units of six warheads each, of average yield Y. We take

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*See Secretary Schlesinger's report to Congress, 10 January 1974. Also see *Offensive Missiles*, Stockholm Paper 5, Stockholm International Peace Research Institute, 1974.

†W. A. Barbieri, *Countermilitary Potential: A Measure of Strategic Offensive Force Capability* (U), The Rand Corporation, R-1314-PR, December 1973 (Secret Restricted Data). CMP is the exponent in the usual kill probability formula. That is, for a single weapon, $\mathrm{KP} = 1 - (1/2)^{\mathrm{CMP}/f(H)}$, where f(H) is a function of target hardness. More refined formulas use vulnerability numbers for susceptibility to blast damage, distinguishing between overpressure and dynamic pressure responses. It will be seen that this gloss is not relevant in this study.

‡We realize that this does violence to Barbieri's explicit summing.

$y/Y = 3$. This means that we are using a Red to Blue *EMT* ratio of about 1.5 for the end of 1974. Since $6 \cdot Y^{2/3} \doteq 3 \cdot y^{2/3}$, the homogenized unit has the same *EMT* strength for both sides. Hence in *CMP* ratios we need use n and N only. We assume further that agreements through 1982 will hold these *numbers* of units fixed, preserving the Soviet EMT advantage.

Next, we assume that CEP is *inversely* proportional to the general level of military technology E (defined below) for Blue and e for Red as of any particular year. Since the proportionality constant is irrelevant in ratios, we take finally for the strategic power ratio

$$p/P = (e^2 n)/(E^2 N) \ ,$$

where as noted $n = 1500$ and $N = 1000$, although modernization will be permitted, changing E and e for the modernized component. Jumping off from CEP in this way is a *rationalization* for a *generalized* strategic power, $E^2 N$.

Assume next that cost* is proportional to the technological level embodied.

$$m = e \cdot n \ , \qquad M = E \cdot N \ .$$

Now try to relate computer technological levels to the military technology levels E and e. What could be its contribution in the large?

A frequently made assumption for the growth rate of a technology is that $dE/dt = K \cdot E$. That is, the acceleration of ℓnE is 0, $d^2(\ell nE)/dt^2 = 0$. This is, perhaps, a simplification of a deeper idea. Consider the propulsion technology sequence: piston engines; turboprop engines; jet engines; ramjet engines; .... The growth in performance in each category follows a logistics or S-shaped curve which is initially almost exponential but then falls off in growth rate as

*These drastic simplifications of cost and effectiveness can be faulted by citing *specific* component technologies. Our intent is to capture *overall* functional dependence as simply as possible.

some asymptote--the physical limitations in that category--is approached. But the envelope to the left of these successively higher curves is approximately exponential, so that for the technology class over time $E = E_0 \exp(Kt)$ and is the leading edge of this class of technology.

Assume that computer technology modifies this process in an essential way, overarching military technology as a whole, and that it gives ℓnE a positive acceleration. Hence

$$\frac{d^2 \ell nE}{dt^2} = K , \qquad \frac{dE}{dt} = KEt , \qquad E = E_0 \exp(Kt^2/2) ,$$

$$\frac{d^2 \ell ne}{dt^2} = k , \qquad \frac{de}{dt} = ket , \qquad e = e_0 \exp(kt^2/2) .$$

But the acceleration factors K and k are small.* We must assign values to them.

Based on historical and projected curves for the growth in computing power measured in terms of instructions per second and memory size,† we assume that this power has been doubling and will continue to double every six years in the United States, but only every ten years in the Soviet Union.

Solely for this reason, take $K/k = 10/6$. The final step is again not empirically justified or perhaps even justifiable. It is based on an intimate acquaintance with the growth in capability of weapon systems since 1941. The values $K = .0025$ and $k = .0015$ are chosen, since they yield values for E and e which seem intuitively about right. We have no other defense for the choice.

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*Strictly speaking, the integration would yield $E = E_0 \exp(K' t + Kt^2/2)$. Lacking empirical justification for the acceleration surmise, we have used the simpler form.

†See R. Turn and A. E. Nimitz, *Computers and Strategic Advantage: I. Computer Technology in the United States and in the Soviet Union*, The Rand Corporation, R-1642-PR, May 1975.

The following table* gives then the military effectiveness coefficients to be used in the examples. The base year is 1950, corresponding to $t = 0$, and $E(0) = e(0) = 1$.

Year	E(t) (U.S.)	e(t) (S.U.)
1965	1.35	1.19
1967	1.46	1.26
1972	$1.86^{(2)}$	1.46
1974	$2.09^{(3)}$	1.56
1976	$2.36^{(4)}$	$1.68^{(1)}$

This means, roughly, that military technology is doubling every 24 years in the United States and every 30 years in the Soviet Union.

We shall assume that all new U.S. forces introduced between 1974 and 1982 embody on the average the 1976 level of 2.36, since the absorption time for new technology is long.

For the Soviet Union, we will consider four possibilities: autarkic (no help) case (1) and the three cases (2), (3), and (4) where by external help the Soviet Union can embody 1972, 1974, and 1976 U.S. technology in the systems they procure during 1974-1982.

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*These are not exactly the values produced by the exponential formula. They were actually calculated by

$$E(t) = \prod_{\tau=0}^{t} [1 + .0025\tau] \quad \text{and} \quad e(t) = \prod_{\tau=0}^{t} [1 + .0015\tau] .$$

III. THE EXEMPLARY GAME

In essence, the last section argued that official thinking in Washington and Moscow will circle about and be bound to the twin nuclei of power and cost, sensed rather than expressed by E^2N and EN, by e^2n and en. The Bohr atom analogy is apt, since the algebraic names mask the fine structure of these nuclei.

We continue the exploitation of the concept, or perhaps fancy, that simplified analysis can expose the bare determinants of decision, while it will neither assert what decisions should be made nor predict what decisions will be made.

In this spirit, we formulate a one-move, non-zero-sum, two-person game, introducing utility functions as third nuclei.

At the end of 1974, Blue* has 1000 homogenized units of average technological age 1967 ($E_* = 1.46$). Red has 1500 of average (Red) age 1965 ($e_* = 1.19$). Then assuming equal power,

$$E_*^2 N_* = e_*^2 n_*$$

$$P_* = p_* = 2125 \ .$$

Blue's move is the choice of how many units N at a level of $E = 2.36$ to introduce at a uniform rate during 1974-1982. The force size $N + (N_* - N)$ is held constant by retiring older units, and N does not exceed 1000, representing a SALT-type agreement. Blue's strategic power in 1982 is

$$P = AN + 2125 \ , \qquad A = E^2 - E_*^2 \ .$$

A is the marginal power added per new unit. Blue's *incremental* cost is

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*Blue and Red are used to indicate that these are abstract players.

$$M = \alpha EN + \frac{\beta}{2}(E - E_*)N ,$$

where α is a procurement coefficient and β is a total operations charge over eight years. Take $\alpha = 10$, $\beta = 2$ as plausible values. Then

$$M = B \cdot N , \qquad B = 24.5$$

in arbitrary budget units. B is the marginal cost per new unit.

Red's choice, made simultaneously with Blue's, is how many units n to introduce. As mentioned above (p. 7) there will be four cases (four values of e). The value of e is not chosen by Red. It depends on the amount of external help received. Then for Red,

$$p = a \cdot n + 2125$$

$$a = e^2 - 1.42$$

$$m = b \cdot n$$

$$b = 11 \cdot e - 1.19 .$$

The values for Red are

Level	e	a	b
Autarky	1.68	1.41	17.3
1972	1.86	2.05	19.3
1974	2.09	2.93	21.8
1976	2.36	4.15	24.5

Note that for 1976 case, Red gains more in power (4.15) per new unit than does Blue (3.44) because he is retiring older and less-effective units. Note also that to get comparability in relative drain on resources we have used the same procurement and operations coefficients (α and β) for both. Red would gain if a more reasonable β (say 1) were used for him, since he has much lower operating and support costs.

Two utility functions U(p, P) and u(p, P) are now needed, giving the desirability to Blue and to Red, respectively, of a game outcome (p, P). These functions are assumed to be known to both players. U and u, as will be seen, can actually be expressed in money, but of course no money changes hands--utility is not transferable in this formulation. In a non-zero-sum game, one player's loss is not his opponent's gain.

The utility functions relate the Red to Blue power ratio and cost to each. The cost M (to Blue) is a linear function of P, upon elimination of N, and similarly for Red. Write the utility functions in the functional form

$$U = GF(r) - P \ , \qquad u = gf(r) - p \ ,$$

where $r = p/P$. F and f represent the utility of the power ratio r to Blue and Red. P and p can be thought of as representing costs, since results in non-zero-sum game theory do not change if the utility functions are independently multiplied by constants and have constants added to them. P and p are proxies for costs. Thus there is decreasing utility to each player as the military budget, expressed as *absolute* strategic power, increases.

Blue considers r = 1 to be parity, a situation of Mutual Assured Deterrence (MAD), and does not view a *slight* increase in r with much alarm. But as r approaches 2, Blue sees a catastrophic strategic imbalance looming. Hence F(r) is concave downward, falls, and has a negative second derivative.

Red, or at least the Red military community, is not happy with r = 1 and would like to make it 2, considering this an *assured disarming* deterrent against Blue. But Red's domestic sector is more and more resistant to the expense as r approaches 2--enough is enough. So f(r) is also concave downward, has a negative second derivative, but *rises*, and is probably flat at r = 2.*

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*See Appendix B for an expanded discussion of these utility functions. We must note that the assumptions about national perceptions leading to these utility functions are intuitive, and are not the result of any extensive policy or intelligence analysis. See the Critique section for further comment.

It remains to consider the coefficients G and g. Shifting gears again, replace P and p in the second terms of the utility functions by the costs M and m. The first terms must also have the dimensions of money. Hence G and g have the dimensions of money per unit of risk and money per unit of superiority, respectively.

Go back once more to the forms $G \cdot F(r) - P$ and $g \cdot f(r) - p$, as a matter of convenience in discussing the adopted solution concept for this game. We shall use the "non-cooperative" approach.* It is essential to note that "non-cooperative" does not mean a rejection of negotiation in the real world. We argue that the utility functions and the risk propensity coefficient G (advantage coefficient g) capture the possible outcomes of negotiation, successful or unsuccessful. (For example, dropping the conspiratorial "we," I believe that at the time of SALT ONE, the Russians were ready to level off force size as a purely internal decision, while maintaining compounded growth in their R&D establishment, in the interest of a deferred rise in r.) We remark that this analysis emphasizes the role of technology, permitting the force *sizes* though not costs to stay constant.

We take the position that each player is trying to maximize his own utility function, the Hegelian imperative for States. Then Blue says, "whatever p Red *should* choose, I will choose P as a function of that p to maximize my utility U." Similarly Red will choose p(P) to maximize u. Let (p_0, P_0) be the solution of these two equations $P = P(p)$ and $p = p(P)$. This is called the equilibrium point and is the noncooperative solution concept.

As shown in Appendix A, the value of $r = p/P$ at the equilibrium point is the root of the equation

$$\frac{g \cdot \frac{df}{dr}}{G \cdot \frac{dF}{dr}} = - r$$

and

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*See Appendix A for a fuller discussion of game theory including the "cooperative" solution concept.

$$p = -G \cdot r \cdot \frac{dF}{dr}$$

$$P = g \cdot \frac{df}{dr} .$$

The game is noncooperative in that the players do not *agree* on the equilibrium point. They are independently driven to it by self-interest. If one player abides by it in his choice, the other cannot do better than abide by it also. In this sense, we consider the solution concept descriptive of behavior rather than normative for it.

We can now start pulling the threads together. Using the expressions for P, p, M, m at the beginning of this section, we rewrite the earlier equations for U and u as

$$U = G \cdot F\left(\frac{a \cdot n + \nu}{A \cdot N + \nu}\right) - B \cdot N$$

$$u = g \cdot f\left(\frac{a \cdot n + \nu}{A \cdot N + \nu}\right) - b \cdot n$$

where $\nu = 2125$, $A = 3.44$, $B = 24.5$, and a and b are case-dependent.

No further progress can be made without specifying F(r) and f(r). The simplest functions with the desired properties are*

$$F(r) = r - r^2 \qquad f(r) = 4r - r^2 .$$

Using these expressions, we have

$$\max_N U: \quad G \frac{df}{dr} \cdot \left(-\frac{A}{B} r\right) = AN + \nu ,$$

$$\max_n u: \quad g \frac{df}{dr} \left(\frac{a}{b}\right) = AN + \nu ,$$

$$r \frac{dF}{dr} + \rho \frac{df}{dr} = 0 ,$$

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*We feel that analysis of this nature should go as far as possible using general functional forms for utility, to see what underlying mechanisms may be driving conclusions.

$$\rho = aBg/AbG = \frac{r(2r - 1)}{2(2 - r)} , \qquad G = \frac{aB}{Ab} g \cdot \frac{2(2 - r)}{r(2r - 1)} ,^{*}$$

$$N = \frac{2a}{Ab} g(2 - r) - \frac{\nu}{A} , \qquad n = \frac{2}{b} gr(2 - r) - \frac{\nu}{a} .$$

Measuring g in units of 10,000,

Autarky:	$N = 474\ g(2 - r) - 618$
	$n = 1156\ gr(2 - r) - 1507$
1972:	$N = 616\ g(2 - r) - 617$
	$n = 1037\ gr(2 - r) - 1039$
1974:	$N = 783\ g(2 - r) - 617$
	$n = 919\ gr(2 - r) - 724$
1976:	$N = 974\ g(2 - r) - 617$
	$n = 807\ gr(2 - r) - 512$

(Multiply by B respectively b to get incremental costs.) In all cases, we require $0 \leq N \leq 1000$, $0 \leq n \leq 1500$, which places a restriction on g.

Figure 1 plots the equilibrating N and n for g = 2 and variable G. Figure 2 is similar but plots incremental costs $B \cdot N$ and $b \cdot n$. The latter plot is more meaningful, since it reflects increasing costs to Red for higher technology levels. We shall discuss these plots.

When both Blue and Red embody 1976 technology, Blue's maximum permitted modernization of 1000 units occurs at a little less than r = 1.2 (Fig. 1). Hence in Fig. 2 we stop the plots at this point. Note that Red always modernizes considerably less than his maximum force of 1500 units. We stop Red's curves to the right where Blue does not modernize any units. Of course, these curves are read by pairs, corresponding to one of the four cases as labeled.

The broken lines for which G = constant have meaning only where they intersect Blue's solid lines. As one would clearly expect, for Blue to reduce the adverse strategic power ratio, he must stress more and more his risk propensity coefficient G, and so pay more.

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*Hence the case and selected r determing G/g.

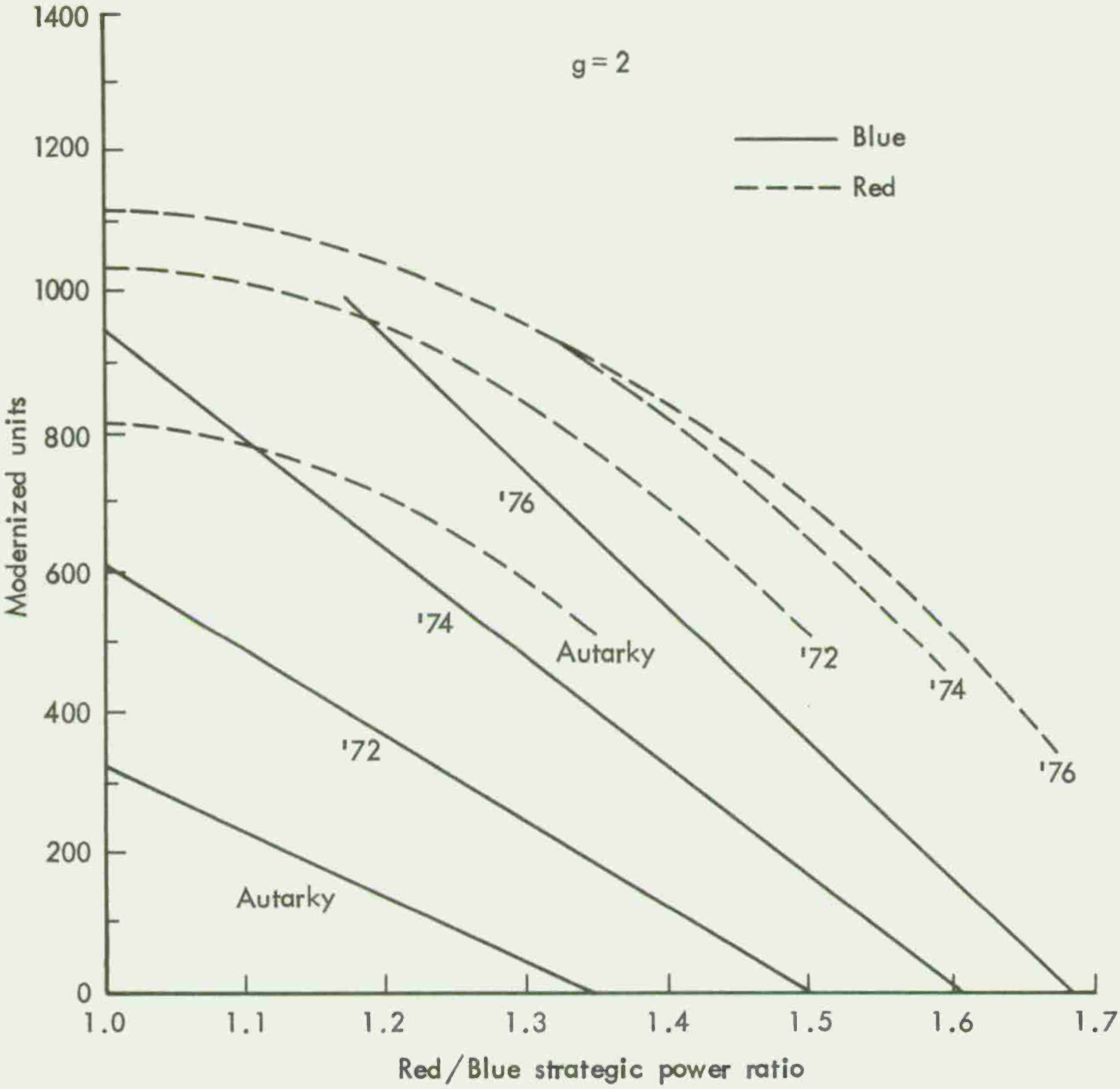

Fig. 1 — Non-cooperative equilibria

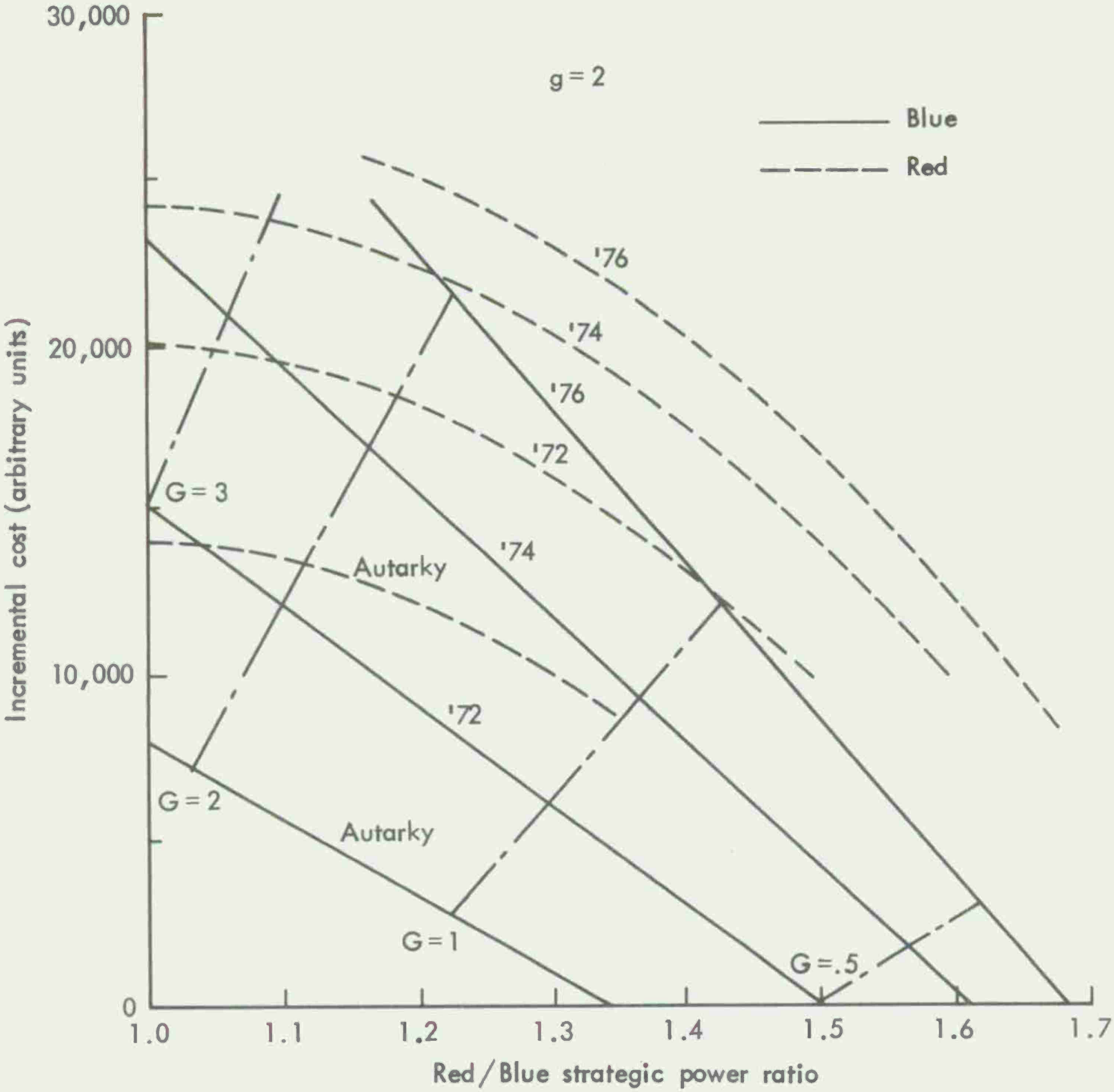

Fig. 2 — Non-cooperative equilibria

Here we part company radically with conventional game theory. In that theory, the utility functions are fixed as part of the games definition and the solution r is computed, and one is done. We move in an opposite direction. If Blue does not like a solution r, he must reassess the coefficient in his utility function. The point is worth more thinking through.

We see the real gain to Blue in having a technology lead. Suppose we want strategic "equality," r = 1. Then in the autarkic case Blue modernizes about 33 percent of his force, and Red 54 percent, with Red's cost 1.72 that of Blue.

However, if Red has a 1974 technological level, these numbers change to 95 percent, 74 percent, and 1.04, respectively. But this conceals the impact of the technological "arms race." In the 1974 case, Blue spends almost three times as much as in the autarkic case. Red spends 1.75 times as much. And the absolute expenditures are close to equality, with nothing achieved, since the ratio stays at unity.

If Blue is willing to settle for, say, r = 1.2, the technological arms race is ameliorated for all cases, but the pattern of increasing relative penalty to Blue is still clear. We view these charts as background for policy decision. If the reader wants to play seer, he is invited to intuit his own course of strategic events and decisions and mark his own 1982 points on the charts. That is, he can assess a value for G and a level of technology transfer as he thinks these will occur, and see what value of r will occur.

It is *now* easy to say that the chart patterns are obvious, without the potpourri of assumptions and techniques that generated them. Of course, *the stronger the Soviet Union technologically relative to the United States, the more both will have to pay if the ratio of their strategic power is driven lower, even under SALT limitations on numbers*. But was it so obvious? Moreover, one objective of policy analysts is the attempt to *quantify* such words as "stronger," "more," "lower," and "numbers" in the just italicized statement, which is of course the conclusion of this analysis.

The policy implications are these:

1. As conventional wisdom has it, it is very much in the interests of the security of the United States and of the drain on the federal budget to maintain as great a technological lead over the Soviet Union as possible.
2. In the negative direction, we should not give our most advanced computer technology to the Soviet Union and we should try to prevent our Allies from selling theirs.
3. In the positive direction, we should greatly increase our own already large investment in computer technology, not only as a hedge against the not unlikely failure to keep current technology from the Russians, but for reasons more persuasive and deeper than strategic power ratios.

The last point is a major theme of the last section.

IV. CRITIQUE

We promised that in this last section we would mount an attack against the strategic power ratio employed in the analysis, and would show why the United States needs greatly increased computing power.

To commence, computer technology permeates all phases of the development, production, operation, and support of modern military systems. Six dimensions can be nonexhaustively distinguished and illustrated.

1. *Research and Development.* Computers permit a major saving in time and resources. This is evident in the design of aircraft, missiles, and new warheads. Prototyping and laboratory study can be partially displaced, with the presumed result that a better device is achieved, although the temptation to over-engineer is rarely resisted.
2. *Production.* Computer-aided design and production processes and quality control improve the product, minimize waste, and lead to systems less apt to malfunction in an operational environment. The effect is to increase effectiveness by having more units operational.
3. *Support and Maintenance.* Electronic data processing again enhances effectiveness by providing a higher percentage of machines in an operationally ready state at any time, preceding both commitment to operations and recommitment after sortie recovery, at least for aircraft.
4. *Onboard Computers.* These devices permit one machine to do each of several missions better than a mix of simpler, mission-specialized machines. Onboard computers may permit targeting not otherwise possible, such as the redirection in flight of a missile to a target acquired during that flight. Certainly such computers lead to improvements in CEP.
5. *Tactical Fragging.* Effectiveness increases when the time of the cycle--target acquisition, designation, force commitment,

ordnance loading, routing, communications, recovery--is decreased while its precision is increased. That is, forces not committed on a timely basis are in effect temporarily useless.

6. *Command, Control, Communications (Strategic Fragging).* It is evident that if a C^3 system deploys a sensor system which in real time can perform damage assessment, determine residual enemy force posture, provide empty-hole information, perform boost-phase and midcourse tracking to determine own forces at risk, evaluate the evolving enemy main battle plan, exercise fingertip control over own forces, and reoptimize plans, then strategic force effectiveness increases because of more effective applications and less waste of combat capital.

Of course, as computer technology permeates it also increases costs, although alternative ways of getting benefits may be much more costly. Because of tradeoffs between quality and quantity, careful, nonaggregated costing must play its role in strategic modeling, as it must in actual posture decisions.

Costing must be done at least by classes of weapon systems. Cost per unit will certainly be a function not only of computer technology embodied but also of other advanced technologies employed. Position on the learning curve (average cost decreasing as more are bought), commonalities, and support structure are also significant determinants of costs.

In the strategic power index used in this report we have reflected at most one of these six dimensions--onboard computing to improve CEP. Going beyond this, if the overall reliability of Blue's ICBM force, because of all dimensions, is 80 percent and that of Red only 60 percent, then these percentages should multiply the ICBM components in the power ratio, modifying it greatly in Blue's favor.

Similar remarks apply to bomber penetration and target selection, particularly for the powerful Blue bomber force. On the other hand, we may have to penalize the Blue SSBN force if Red fields a major ASW force--denial of ocean areas to Polaris and Poseidon boats by heavy,

sophisticated mining, armed sweeps by MAD aircraft over the restricted operational areas of these boats, massive overt trail of the wide-ranging Tridents by SSNs. In sum, the power ratio employed does not allow for operational factors and defense[*] both of which are highly computer-dependent. The ratio does not portray actual war-fighting and its timing.

It is, in fact, by looking at the command, control, and communications domain that we see most clearly why the ratio is meaningless as a measure of the *outcome* of counterforce war. Only one major dichotomy is needed to make the point.

Under the assumption that Red would go first in an attempted assured disarming strike against Blue, there is a major asymmetry in the ICBM duel. Since Red goes first, he can implement a carefully planned SIOP. But Blue must be reactive. Because of the change in target system status as a result of Red's commitment of forces and because of initial decimation of Blue's force, Blue must dynamically reoptimize *his* prepared SIOP, retarget, reprogram, and retime his Triad forces. Suppose this takes hours. The possibility opens for Red to use a shoot-look-shoot strategy, disrupting anew the reactive SIOP.

Now as the logical alternative, suppose Blue's computer capability is such that he has the valid option of launching his entire missile force in 15 minutes, exploiting his empty-hole information and retargeting and reprogramming his missiles *in flight* against enemy holdback forces and other time-urgent targets.[†] The computer demands on Blue are heavy. To accomplish these functions and all the others in an

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[*]Each ICBM killed subtracts up to three RVs from the counter-military potential, each bomber lost subtracts six gravity bombs or more SRAMs, and each SSBN killed subtracts 160 RVs.

[†]The standard (mistaken) arguments against launch-on-warning are "warning is ambiguous, we may precipitate catastrophe" and "even if this is not so, launching against enemy cities will again mean our own annihilation." The first is no longer true, with our multiple sensor systems, and in respect to the second, the launch is *in kind*, against military targets. The deeper argument that missile wings could be pinned down by continuous SLBM bombardment until Red missiles arrive, is countered by the calculation of megatonnage required, eating too deeply into resources needed for attack against SAC.

airborne command post in less than missile flight time will require of the hardware perhaps 50 million instructions per second and one billion bits in fast memory,* these being the demands of the software's monstrous appetite. (See Appendix C for schematic transattack functions.)

This alternative has two stabilizing consequences. First, Red is deterred. Why should he waste his resources against targets that will be nonexistent on his arrival. And second, using the usual paradoxical logic, should he actually launch a first attack, the U.S. missile force required to strike enemy holdback forces is much smaller than one which must be able to absorb the first blow and still have enough left for the holdback attack mission.† As a corollary, such a reduced force does not have a valid first-strike capability of its own, confounding those who fear this. It can be as accurate as technology can make it.

As qualified earlier, the strategic power ratio is a Cheshire cat--only an impressionistic representation of the outcome of counterforce war remains. But we still think that something much like it will drive strategic thinking. And, on reflection, if fine grain studies were made of the minute-by-minute interaction in counterforce war of strategic forces varying in size and *explicit* technological capabilities, it is not beyond belief that a strategic power ratio could be shown to be an acceptable surrogate for detailed outcome calculations.

To conclude the Critique, two technical questions are put:

Does a simple utility function with a few attributes capture the essence of decision, the outcome of overlapping and complicated domestic bureaucratic games?

This is largely a new area of mathematical political science, well worth cooperative debate by students of Washington and Moscow.

If the utility function notion proves viable, the assessment of relative weights of attributes (such as G and g) should fall out of the analysis. Historical studies will be useful.

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*We are unable to substantiate this overall estimate on an unclassified basis. The flowcharts of Appendix C should make this reservation acceptable.

†The experienced reader will detect flaws in the argument as presented, which, of course, we will not spell out. We hope to elaborate on the dichotomy in other writings.

Is the noncooperative game formalism an acceptable gross representation of real U.S./Soviet interaction?

For the past, the answer could well be "yes," since as the Soviet strategic budget rose in real terms, the U.S. budget, also in real terms, tended to fall. To me, this means particular utility functions independently maximized. In an era of so-called détente, I suspect that we need a new game-theoretic construct, that of a semi-cooperative game.

Appendix A

EINE KLEINE SPIELMUSIK

Appendixes A and B are largely tutorial in nature. We hope that a wider class of analysts will examine the applicability of these concepts to the study of policy questions.

In a one-move game, simultaneously Blue chooses a number P and Red a number p. The (cardinal) utility (or payoff) of the choice (p, P) is U(p, P) for Blue and u(p, P) for Red. These utilities are nontransferable. That is, unlike a zero-sum game, what one loses the other does not win, and moreover no side payments to induce particular behavior can be made. Utility measures the subjective desirability of various outcomes as viewed independently by the players.*

Suppose the players do not discuss their choices prior to making them, and do not concert their decisions in any way. This is the noncooperative game. Each wishes only to maximize his own utility. For each p, Blue determines P = P(p) to maximize U(p, P), and similarly for each P, Red determines p = p(P) to maximize u(p, P). There is now, however, joint leverage. Let (p_0, P_0) be a solution of the equations P = P(p) and p = p(P). (In our applications to come (p_0, P_0) always exists and is unique.) The choice (p_0, P_0) is called the equilibrium point. It dictates a joint rule of behavior such that if one player abides by it the other player cannot do better than abide by it also. For

$$U(p_0, P) \le \max_P U(p_0, P) = U(p_0, P_0) \ , \qquad \text{all } P \ ,$$

$$u(p, P_0) \le \max_p u(p, P_0) = u(p_0, P_0) \ , \qquad \text{all } p \ .$$

---

*All results are invariant under independent linear transformations on the utilities.

On the other hand, suppose Blue and Red discuss their choices to see if they could both do better were they to cooperate.* First, as in Fig. 3, plot U versus u, using p and P as parameters. Moving from any internal point northeast to the boundary means both players do better. This boundary, along which $dU/du < 0$, is the Pareto frontier. Moving along it, as one player gains the other loses. The cooperative value solution should lie on this frontier.

The players agree to a joint maximization of $U + \lambda u$ as an expression of their common welfare. The coefficient λ has two roles. It will measure the relative weight of U and u as the result of "equitable" and "efficient" implicit bargaining, and it is dimensioned to permit the addition of the nontransferable utilities.

How is λ to be chosen, and in what sense is the choice jointly desirable? The players examine a "threat" game $U - \lambda u$, and look for its saddle-point. Blue will try to maximize by choice of P since this means maximizing his utility and minimizing Red's, which is why it is a threat. Conversely, Red will try to minimize this expression.

Now formulate the procedure with cooperative and competitive parts by writing

$$V(\lambda) + \lambda v(\lambda) = \max_{P} \max_{p} [U + \lambda u]$$

$$V(\lambda) - \lambda v(\lambda) = \max_{P} \min_{p} [U - \lambda u] = \min_{p} \max_{P} [U - \lambda u] .$$

Then $(\lambda, V(\lambda), v(\lambda))$ is the cooperative value solution. If the players do not agree on this joint assessment of utilities, they fall back to the enforceable threat point and both do worse.

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*The lineage of the sketch to follow is: Zeuthen (1930--move-by-move bargaining in labor management disputes); Nash (1950--derivation from axioms that the players should maximize the product of their utilities); Hasarnyi (1956--the equivalence of the Zeuthen/Nash procedures); Selten (1964--transferable utility games with cooperative and competitive parts); Shapley (1969--extension to nontransferable utilities).

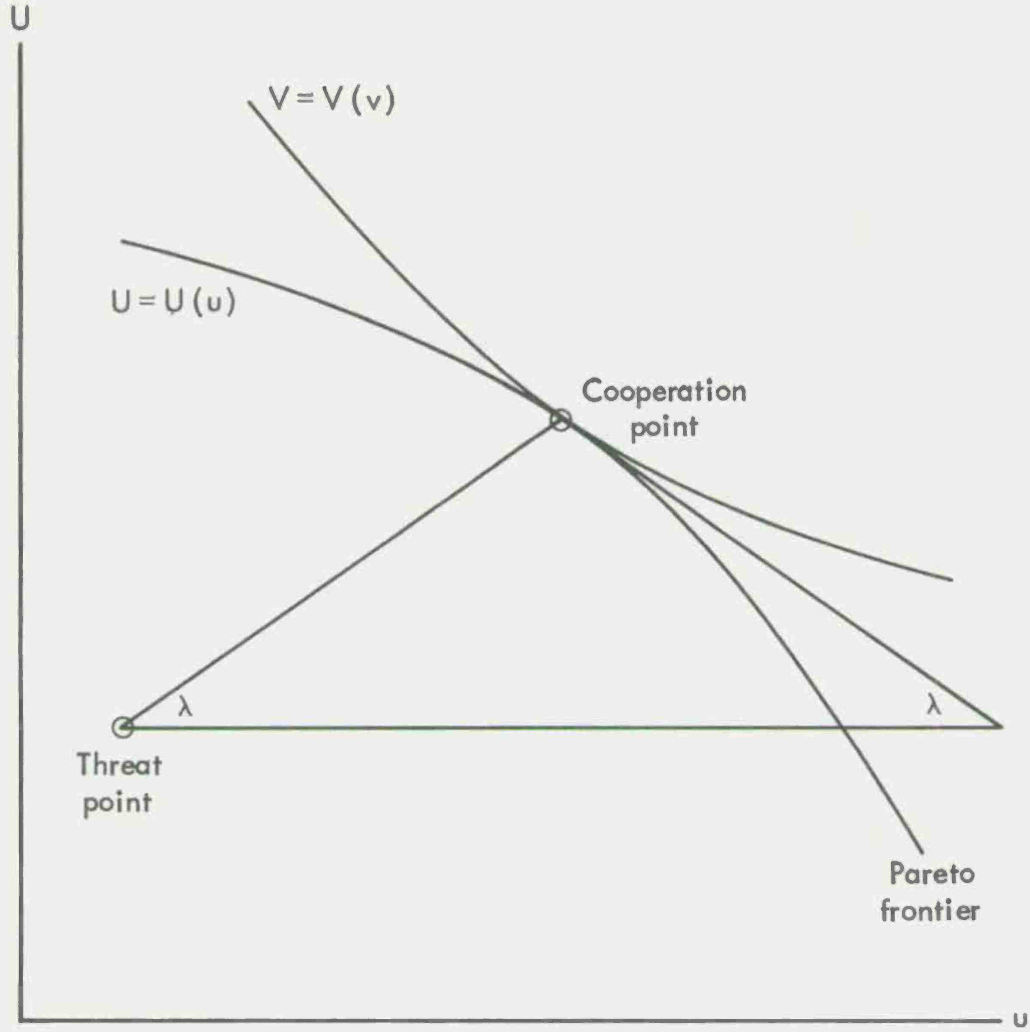

Fig. 3 — Utility space

Figure 3 shows the geometry of the solution. At the point of tangency of $V = V(v)$ and the Pareto frontier $U = U(u)$, $dV/dv = dU/du$. Also

$$V(\lambda) = U\Big(p(\lambda),\ P(\lambda)\Big)\ , \qquad v(\lambda) = u\Big(p(\lambda),\ P(\lambda)\Big)\ .$$

Then

$$\frac{dV}{d\lambda} = \frac{\partial U}{\partial p}\frac{dp}{d\lambda} + \frac{\partial U}{\partial P}\frac{dP}{d\lambda}\ , \qquad \frac{dv}{d\lambda} = \frac{\partial u}{\partial p}\frac{dp}{d\lambda} + \frac{\partial u}{\partial P}\frac{dP}{d\lambda}\ .$$

Because of the max max

$$\frac{\partial U}{\partial p} + \lambda \frac{\partial u}{\partial p} = 0 \ , \qquad \frac{\partial U}{\partial P} + \lambda \frac{\partial u}{\partial P} = 0 \ .$$

Thence

$$\frac{dV}{dv} = - \lambda \ .$$

At the threat point, for the minimum with respect to p

$$\frac{\partial U}{\partial p} - \lambda \frac{\partial u}{\partial p} = 0 \qquad \text{so that } p = p(P) \ .$$

For the maximum with respect to P

$$\frac{\partial U}{\partial p}\frac{dp}{dP} + \frac{\partial U}{\partial P} - \lambda \frac{\partial u}{\partial p}\frac{dp}{dP} - \lambda \frac{\partial u}{\partial P} = 0 \ ,$$

and

$$\frac{\partial U}{\partial P}\bigg/\frac{\partial u}{\partial P} = \frac{dU}{du} = \lambda \ .$$

That is, the slope of the Pareto frontier at the cooperation point is the negative of the slope of the line from the threat point to the cooperation point.

In the application made of the preceding theory we use utility functions of a particular class. (We defer until Appendix B the physical interpretation of these functions.) Require $P \geq 1$, $p \geq 1$, and take

$$U = G \cdot F(r) - P \ , \qquad u = g \cdot f(r) - p \ , \qquad r = p/P \ ,$$

where G and g are constants. F(r) has its first and second derivatives both negative, while f(r) has a positive first derivative and a negative second derivative, so that both are concave downward.

For the noncooperative solution, maximizing yields

$$\frac{\partial U}{\partial P} = G \cdot F'(r) \cdot \left(- \frac{r}{P}\right) - 1 = 0 ,$$

$$\frac{\partial u}{\partial p} = g \cdot f'(r) \cdot \left(\frac{1}{P}\right) - 1 = 0 .$$

Hence

$$\frac{gf'(r)}{GF'(r)} = - r$$

determines r and so p and P.

Turning to the cooperative value solution, at the threat point for the min on p of $U - \lambda u$ we have

$$[G \cdot F' - \lambda gf'] \cdot \frac{1}{P} = - \lambda .$$

Thence for the max on P

$$[GF' - \lambda gf'] \left(\frac{1}{P} \frac{dp}{dP} - \frac{p}{P^2}\right) + \lambda \frac{dp}{dP} = 1 ,$$

$$- \lambda \frac{dp}{dP} + \lambda \cdot \frac{p}{P} + \lambda \frac{dp}{dP} = 1 ,$$

or

$$\frac{p}{P} = \frac{1}{\lambda} = r .$$

Next find the Pareto frontier. Fix r so that $p = rP$. Then

$$\frac{dU}{dP} = - 1 , \qquad \frac{du}{dp} = - r .$$

Hence if $r > 1$, take P as small as possible, or $P = 1$. Also

$$\frac{dU}{dp} = -\frac{1}{r}, \qquad \frac{du}{dp} = -1,$$

so for $r < 1$ take $p = 1$. When $r > 1$, $P = 1$, $dU/du = gF'(p)/[gf'(p) - 1]$. Since $F' < 0$ and $f' > 0$, $dU/du < 0$ if $gf' > 1$. When $r < 1$, $p = 1$, $dU/du = [GF' + P^2]/gf'$. Hence $dU/du < 0$ if $GF'(1/P) < -P^2$.

Turn to the cooperative point. For the max of $U + \lambda u$ on p we have

$$[GF' + \lambda gf'] \frac{1}{p} = \lambda .$$

For the max on P

$$[GF' + \lambda gf'] \left(\frac{1}{P} \cdot \frac{dp}{dP} - \frac{p}{P^2} \right) - \lambda \cdot \frac{dp}{dP} = 1$$

which is impossible. Hence, assuming $r > 1$, take $P = 1$. Then

$$V + \lambda v = GF\left(\frac{1}{\lambda}\right) + g\lambda f\left(\frac{1}{\lambda}\right) - 1 - 1$$

$$V - \lambda v = GF\left(\frac{1}{\lambda}\right) - g\lambda f\left(\frac{1}{\lambda}\right)$$

$$V = GF\left(\frac{1}{\lambda}\right) - 1$$

$$v = gf\left(\frac{1}{\lambda}\right) - \frac{1}{\lambda}$$

$$\frac{dV}{dv} = \frac{GF'\left(\frac{1}{\lambda}\right)}{gf'\left(\frac{1}{\lambda}\right) - 1} = -\lambda ,$$

or

$$\frac{gf'(r) - 1}{GF'(r)} = -r ,$$

for the cooperative value solution. Note that $p/P = 1/\lambda$ is constant along a line segment connecting the threat and cooperation points and that the geometry leads directly to the solution.

If $r < 1$, take $p = 1$. Then

$$V + \lambda v = GF\left(\frac{1}{\lambda}\right) + g\lambda f\left(\frac{1}{\lambda}\right) - 2\lambda$$

$$V - \lambda v = GF\left(\frac{1}{\lambda}\right) - g\lambda f\left(\frac{1}{\lambda}\right)$$

$$V = GF\left(\frac{1}{\lambda}\right) - \lambda$$

$$v = gf\left(\frac{1}{\lambda}\right) - 1$$

$$\frac{dV}{dv} = \frac{GF' + \lambda^2}{gf'} - \lambda \ ,$$

or

$$G \cdot r^2 \cdot F'(r) + g \cdot r \cdot f'(r) + 1 = 0 \ .$$

Depending on G and g, one player or the other will find himself on the adverse side of the ratio.

Figure 4 shows the relation between the cooperative and noncooperative solutions. The cooperative ratio (r_c) is less than the noncooperative ratio (r_n). Also

$$P_T = g \cdot f'(r_c) - Gr_cF'(r_c) \ ,$$

$$P_N = g \cdot f'(r_N) = - Gr_NF'(r_N) \ ,$$

$$P_T > P_N \ .$$

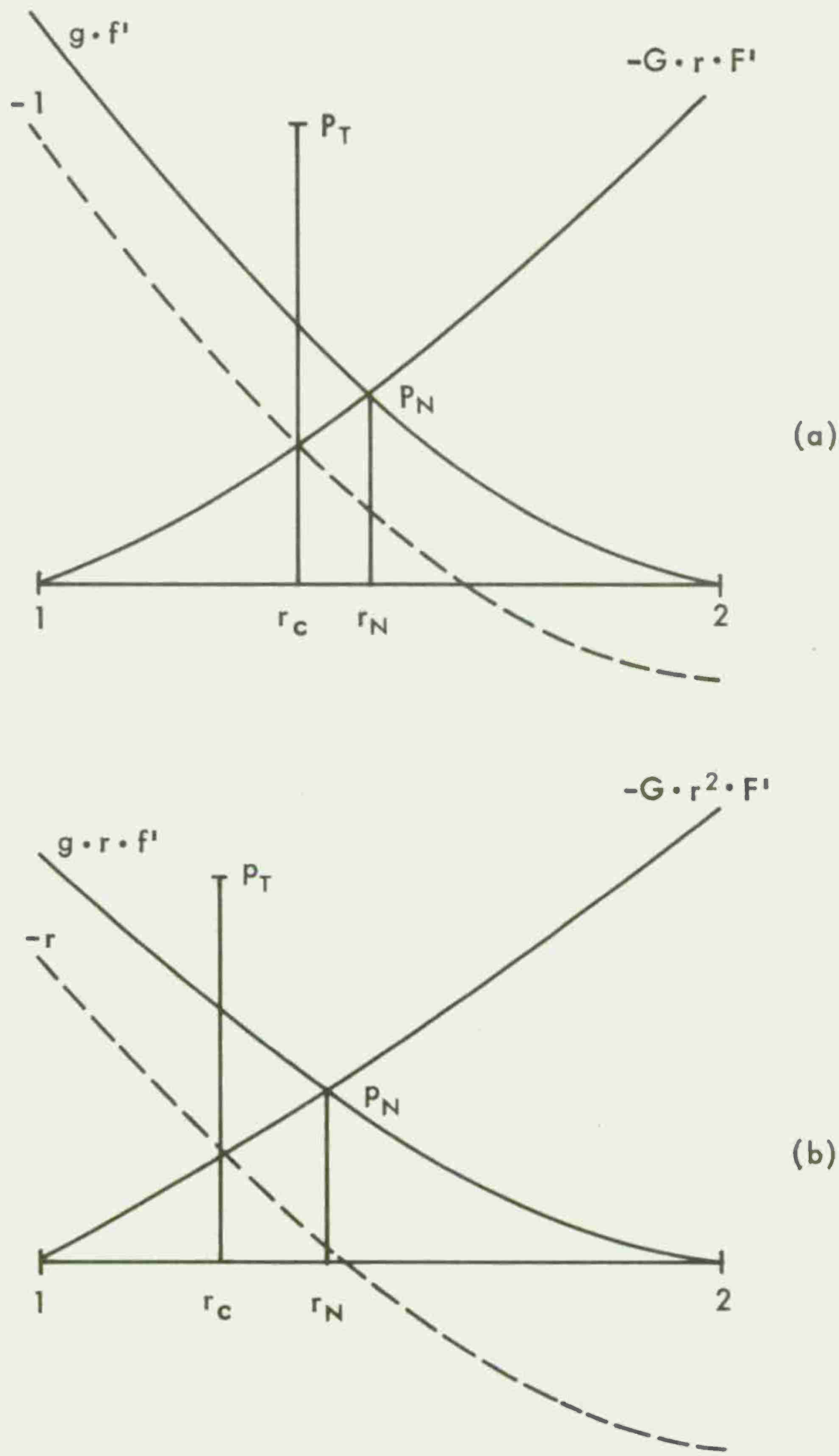

Fig. 4 — Cooperative and non-cooperative solutions

From Fig. 4(b) we have

$$p_T > p_N .$$

Therefore the noncooperative solution is always northeast of the threat point and below the line connecting the threat point to the cooperation point.

We conclude this appendix by discussing the cooperative solution for the exemplary game in the body of the report.

We have

$$U = GF(r) - BN , \qquad u = gf(r) - bn , \qquad r = \frac{an + \nu}{AN + \nu} ,$$

and we use the explicit forms

$$F(r) = r - r^2 , \qquad f(r) = 4r - r^2 .$$

At the threat point, working with n and N, instead of p and P,

$$r = \frac{aB}{Ab} \cdot \frac{1}{\lambda} .$$

At the cooperation point, after first getting $n = n(N)$ by maximizing $U + \lambda u$ with respect to n, we find that the derivative of $U + \lambda u$ with respect to N is negative. Hence we maximize $U + \lambda u$ by taking $N = 0$. We find that the equation for r is

$$2Gr^2 - \left(G - 2g \frac{aB}{Ab}\right) r - 4g \frac{aB}{Ab} + \frac{B}{A} \nu = 0 .$$

For $r = 1$,

$$G = 2g \frac{aB}{Ab} - \frac{B}{A} \nu ,$$

otherwise $r > 1$.

But $r = 1$ means $N = n = 0$, so that neither Blue nor Red modernize forces. If $r > 1$, because G is made smaller by Blue, accepting a greater risk, Red will have a power ratio advantage at low cost.

In some imaginary world Blue might hope to persuade Red to accept those values of G and g in the two utility functions which would lead to $r = 1$ and simply a maintenance of the status quo. But even in this imaginary world, if Red and Blue fail to agree on *joint* maximization of their utilities, they must by the mathematics of that world fall back to a threat point in which, as we have seen, both are worse off than if they had *separately* maximized their utility functions.

We believe the noncooperative procedure is truer to real world behavior and so have adopted it in this study.

Appendix B

UTILITY FUNCTIONS

The utility functions rationalized and then used in the text are

$$U(p, P) = G \cdot F(r) - P , \qquad u(p, P) = g \cdot f(r) - p , \qquad r = p/P .$$

If the Blue and Red utility functions were simply* $F(r)$ and $f(r)$ an undampened arms race would result. For a given noncooperative game, for each p, $\max_P U$ occurs at $\min(p, P^*)$ where P^* is the maximum power Blue can physically achieve in a given time. Similarly for Red for each P, $\max_p u$ occurs at $\min(2P, p^*)$. As shown in Fig. 5, the equilibrium point is at (p^*, P^*). The budget terms supply the dampening.

Why choose the linear form $u_1(r) + u_2(P)$ for the two-attribute utility functions? The answer is illustrated by Fig. 6. Suppose the decisionmaker is indifferent between a 50-50 chance of getting (r, P') or (r', P)--since the utility is the same for both--and a 50-50 chance of getting (r', P') or (r, P)--since the expectation is the same as for the first gamble.† As sketched, this is clearly true. But if the decisionmaker were given the (r, P) quadrant as a *tabula rasa* and expressed the same opinion about the gamble based on a rectangle, then the necessary and sufficient conditions‡ are fulfilled for his utility function to take the form $u_1(r) + u_2(P)$.

(Utility theory uses expectations based on "lotteries" or "gambles." We note (Fig. 6), that the NW/SE gamble has zero spread, whereas the NE/SW can have a large spread. Hence the risk-taking propensities of the decisionmaker may not be properly deduced by this procedure.)

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*Take $F(r) = r - r^2$, $f(r) = 4r - r^2$, $1 \leq r \leq 2$.

†This expectation is *not* at the midpoint of the diagonal.

‡R. C. Fishburn, *Operations Research*, Vol. 13, No. 1, pp. 28-45; *Operations Research*, Vol. 22, No. 1, pp. 35-45. The latter paper gives necessary and sufficient conditions for the five forms: $u_1 + u_2$; $f_1 \cdot f_2$; $u_2 + f_1 \cdot f_2$; $u_1 + u_2 + f_1 \cdot f_2$.

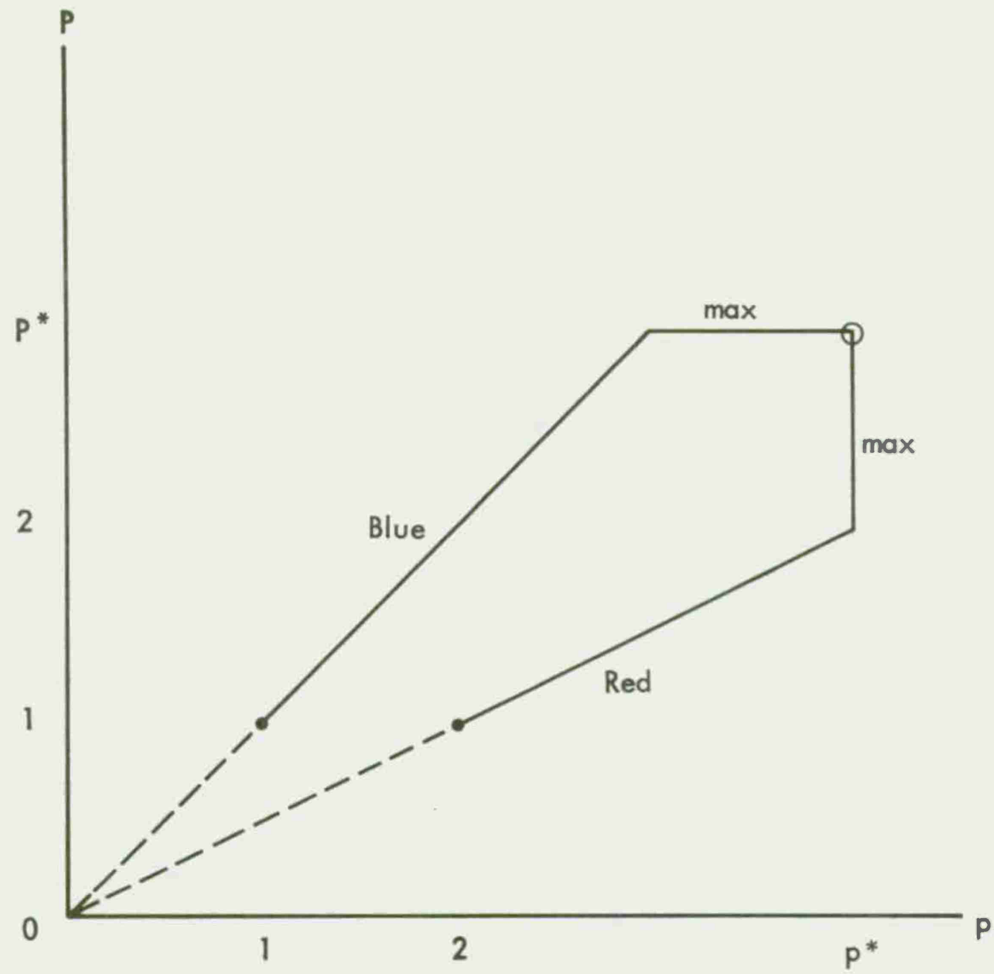

Fig. 5—Arms race equilibrium point

It must be emphasized that one should go as far as possible using only the *Gestalt* of utility function. In a relative sense, consequences are insensitive to the precise algebraic form of F(r) and f(r).

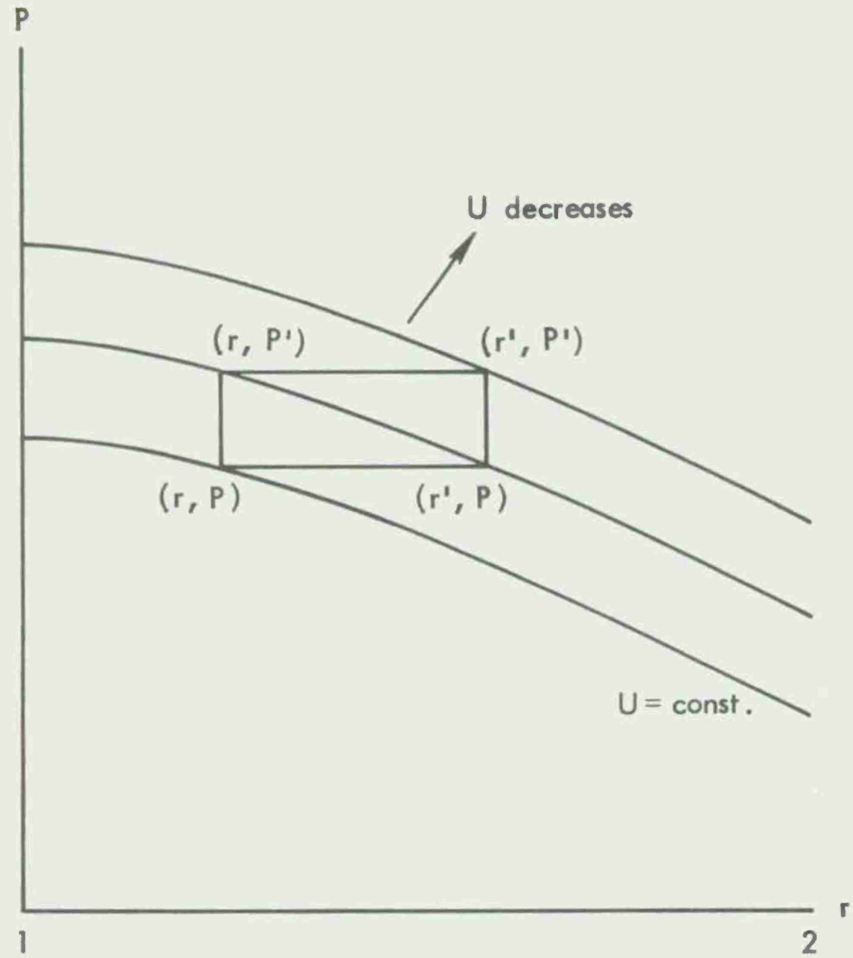

Fig. 6 — Utility lottery

Appendix C

TRANSATTACK FUNCTIONS

Figures 7(a) and 7(b) schematize major functions in a command post versus time for the in-flight retargeting "option." This assumes that large footprint maneuvering reentry vehicles with large onboard target memory are available.

About 20 minutes are available to reoptimize the SIOP. We have found no literature showing how the interplay of the views and information of the National Command Authority and the five CINCs could result in command decision matching this time span.

Other CINC functions require algorithms and data reduction. By the 1980s, U.S. computer capability *could* meet these requirements.

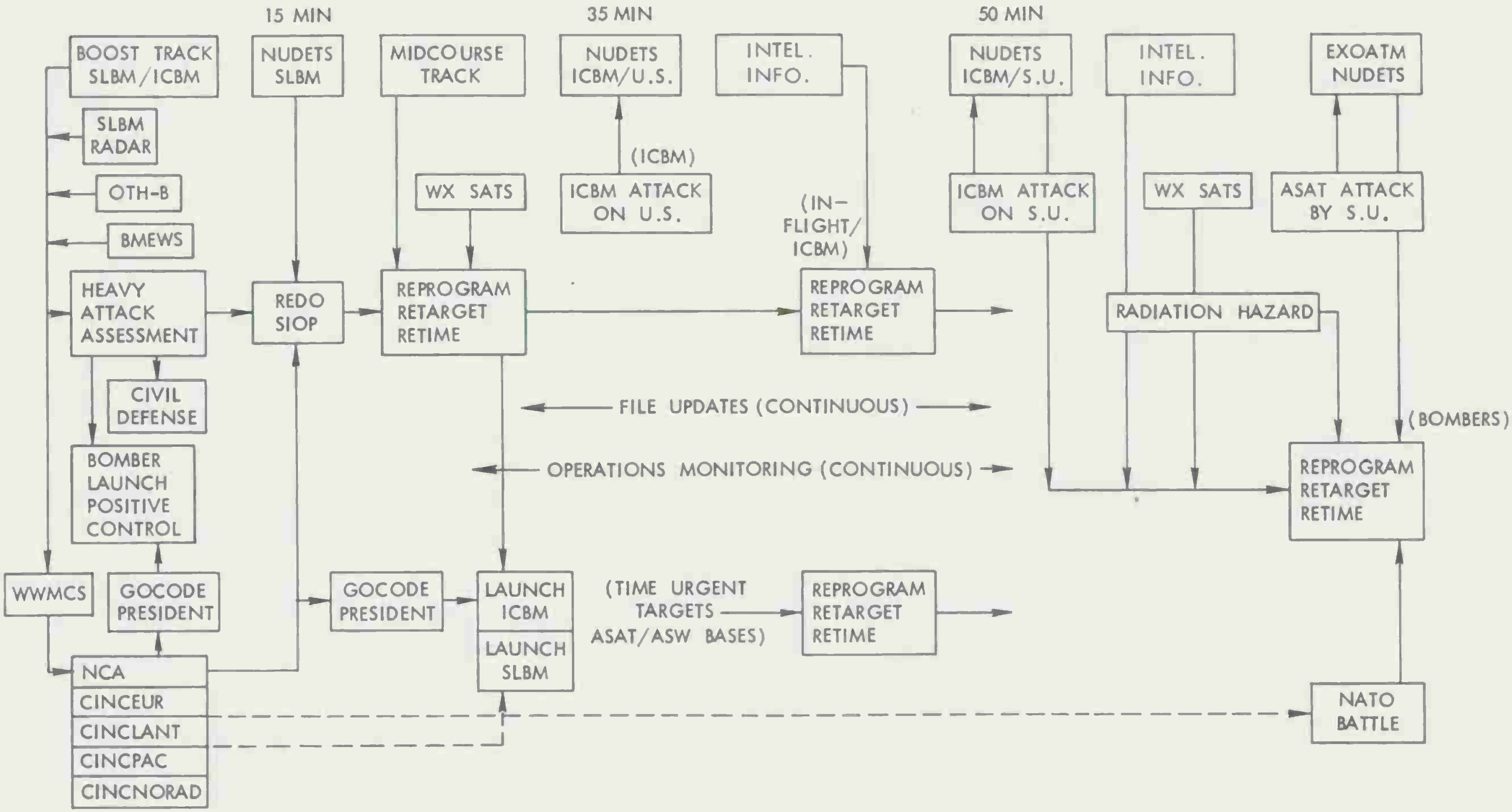

Fig. 7 (a) — Schematic transattack functions

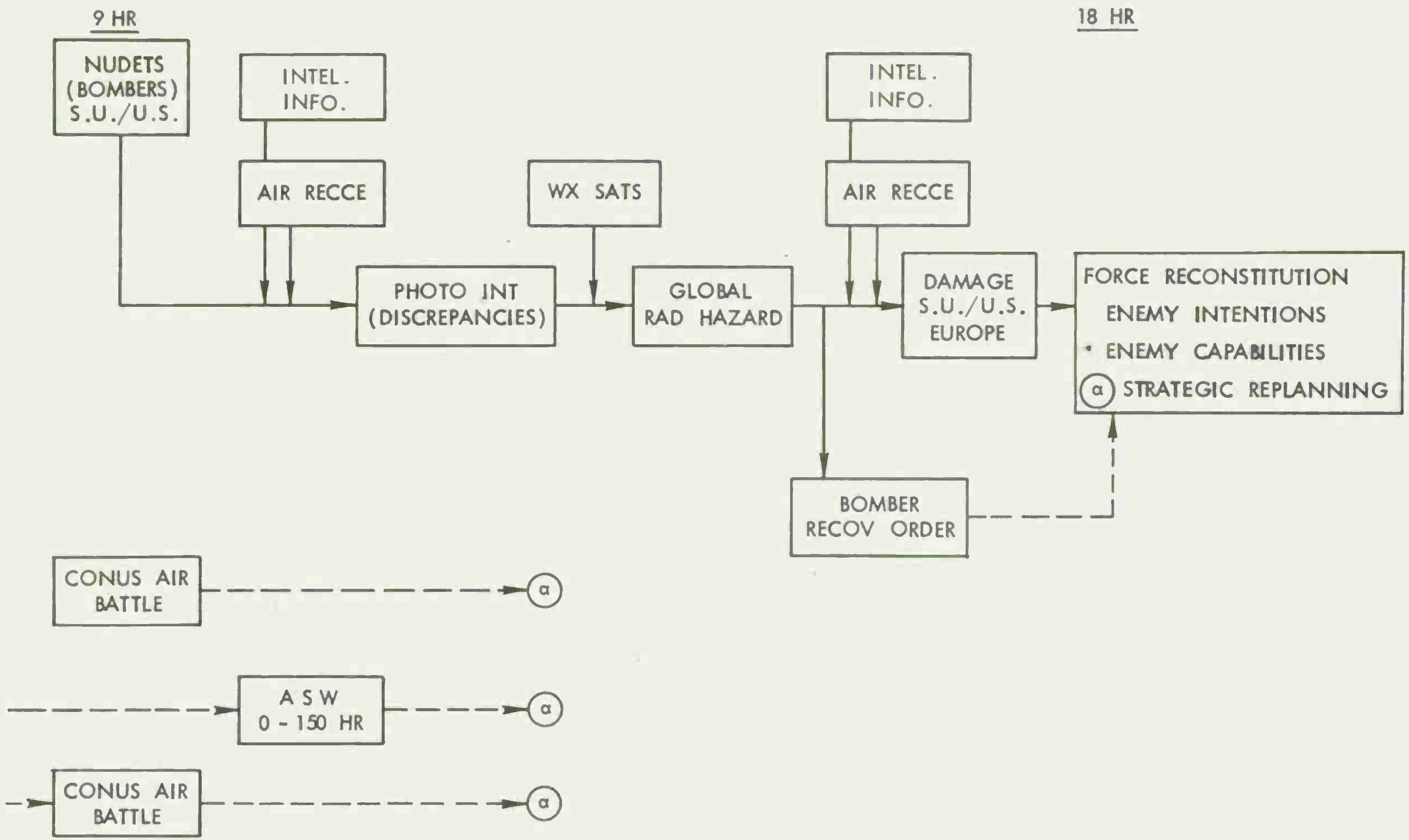

Fig. 7(b)—Schematic transattack functions